10

Promises Fulfilled

"The scientist does not study nature because it is useful;
she studies it because she delights in it,
and she delights in it because it is beautiful."

Henri Poincaré (paraphrased)

ALMA Science Goals

After five years of telescope operation, the ALMA Board formulated a working group to assess the progress toward answering the scientific goals that had established the need for ALMA in the first place. This working group prepared the ALMA Development Roadmap, a vision for the future of the telescope, building on results from its first five to ten years of operations. The Roadmap[1] reported in 2018 that three of the principal science goals had been accomplished, namely:

- *The ability to detect spectral line emission from CO or C^+ in a normal galaxy like the Milky Way at a redshift of $z = 3$, in less than 24 hours of observation;*
- *The ability to image the gas kinematics in a solar-mass protoplanetary disk at a distance of 150 pc, enabling one to study the physical, chemical, and magnetic field structure of the disk and to detect the tidal gaps created by planets undergoing formation;*
- *The ability to provide precise images at an angular resolution of 0.1 arcsecond.*

In contrast to the ALMA Roadmap, the CAA report commissioned to assess the impact of a reduction in the number of antennas on ALMA science had concluded that it would not be possible for ALMA to achieve any of the three science goals with only 50 antennas. This chapter will take a closer look

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at these proposed science goals using specific examples from the roughly 4,000 projects in the ASA at the time of the writing of this book.

Molecular Gas in Distant Galaxies – Further discussion of the first goal was made in an Astro2020 white paper[2] on "Activities, Projects, and State of the Profession Considerations." According to the white paper authored by Crystal Brogan, the first science goal "*has been achieved in spirit, though not in detail – indeed, a major achievement of modern astrophysics is the realization that 'Milky Way-like' galaxies do not exist at $z = 3$.*" That is, the goal was unachievable by definition. The progenitors of a normal galaxy like the Milky Way do exist at $z = 3$ and higher redshifts, and galaxies with the same mass in *stars* as the Milky Way have been detected in CO emission at high redshift. Two early ALMA projects, led by Fabian Walter at the MPIA in Germany and Manuel Aravena at the Universidad Diego Portales in Chile, made these detections, which led to more than 10 publications and were the building blocks for the ALMA Large Program known as ASPECS (ALMA SPECtroscopic Survey in the Hubble Ultra-Deep Field).[3]

The question of whether ALMA met this goal also depends on the definition of "Milky Way-like." If defined as a galaxy at z~3 with the same mass in interstellar gas as the Milky Way, then this has not yet been demonstrated due to the time required for such observations, although it would be less than 24 hours. An even more impressive demonstration of ALMA's power would be to make an image of the CO distribution in a high redshift galaxy that resembles the Milky Way. This would require at least 100 hours of telescope time,[4] a proposition that some astronomers consider "high risk, high reward," but is yet to be done.

Protoplanetary Disks as Sites of Forming Planets – The source HL Tauri emerged as a poster child for the goal of studying the environment of a nearby star in formation and imaging its protoplanetary disk. HL Tauri is a million-year-old Sun-like star located approximately 450 light years from Earth in the constellation of Taurus. It was observed as a test target in 2014, to assess the functionality of the ALMA long baseline capabilities, and several times since then. The first HL Tauri image (Kwon et al. 2011) was obtained using CARMA with baselines up to 1.5 km. The image, shown in Figure 10.1 (bottom panel), revealed a structure in the disk that hinted at early signs of planet formation. The structure had been invisible to previous images, taken with telescopes lacking the resolution of ALMA. See Figure 10.1 (top panel) for an example. The detections were of the emission from the dust, rather than the gas, in the disk surrounding this source. The paper[5] that presented the iconic image of HL Tauri has garnered more than 1,000 citations and counting, making it one of the most prolific ALMA results to date. More than two dozen papers utilizing this verification dataset, and complementary data, have been published since. "*When we first saw this image, we were astounded at the spectacular level of detail. HL Tauri is no more than a million years old, yet already its disc appears to be full of forming planets. This one image alone will revolutionize theories of planet*

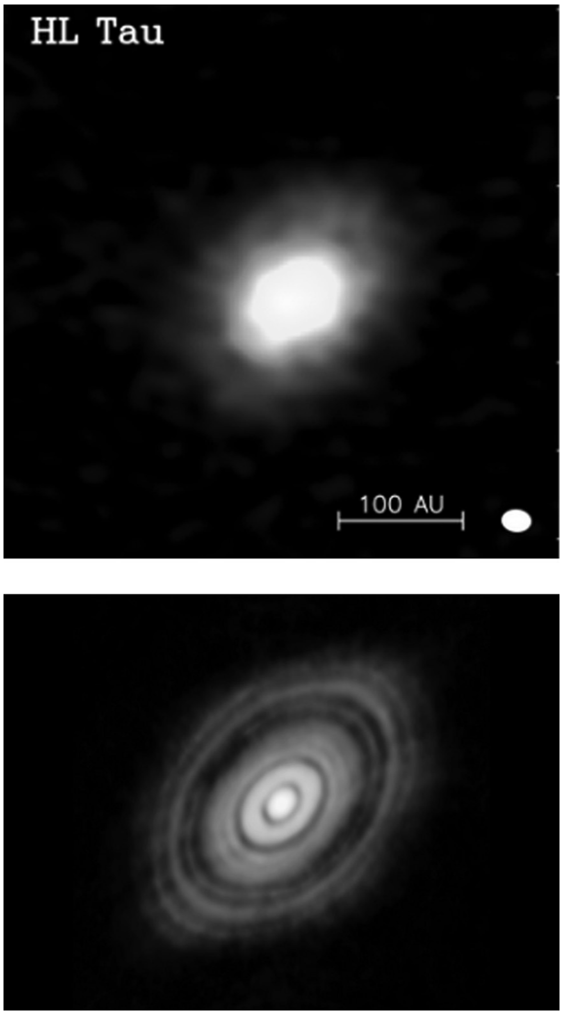

Figure 10.1 Top panel: Image of the protoplanetary disk surrounding the young star HL Tauri, with contours indicating the signal strength, as detected by CARMA before ALMA was built. Bottom panel: The ALMA image reveals the structure of the disk. The gaps are possible locations for planet formation. Credits: (Top) Courtesy of Woojin Kwon, reproduced by permission; (Bottom) ALMA Partnership, et al. (2015); ©AAS, reproduced by permission.

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formation," explained Catherine Vlahakis, who worked at the JAO in Santiago at the time of the observations.

Observations of HL Tauri and other similar sources set the stage for ALMA Large Programs such as the Disk Substructures at High Angular Resolution Project (DSHARP), and later the Molecules with ALMA at Planet-forming Scales (MAPS). The DSHARP program focused on studying the dust and gas (CO) in a sample of twenty relatively nearby, bright, and large protoplanetary disks. The stunning results were presented in a special focus issue[6] of *The Astrophysical Journal Letters*, and showed the distinct and complex shapes and structures at the earliest sites of planet formation. The authors interpreted the observations as evidence for unseen planets interacting with the dust

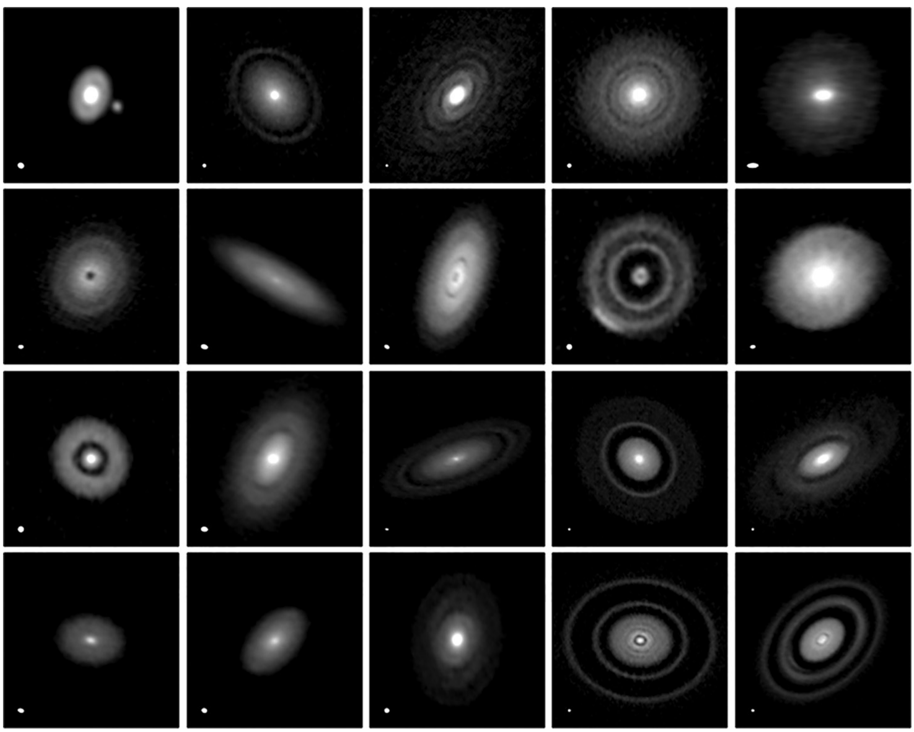

Figure 10.2 Twenty protoplanetary disks imaged by the DSHARP program. This is a groundbreaking gallery of diverse shapes and structures apparent in early stages of star formation, likely pointing to planets forming earlier in the process than previously thought. The small white ellipses in the lower left corner of each panel represent the resolution – or level of discernible detail – of the observations, showing that very minute structures, just about five times the distance from the Earth to the sun, are able to be studied in these images. Credit: Andrews, et al. (2018); ©AAS, reproduced by permission.

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and gas around young stars. This survey confirmed that HL Tauri was not a unique case, but rather, that there were signs of planet formation in nearly all disks observed in great enough detail, based on the concentric gaps and narrow rings that were seen as substructures in the light that was detected. The collection of diverse, spectacular protoplanetary structures, shown in Figure 10.2, was only beginning. It is obvious that ALMA has met its second science goal.

ALMA's Impact on My Career

ALMA has changed the lives of many astronomers in the world, including in Chile. I was lucky to be trained in radioastronomy during research for my master's degree in Chile and for my PhD in France. That gave me the tools to be ready when ALMA was inaugurated in 2013, the same year I graduated. I was fortunate enough to be awarded ALMA observing time during my first postdoc in the United States, which helped kick off my career. I became a frequent ALMA user. I moved back to Chile at the end of 2016 to work at the ALMA headquarters in Santiago, where I was able to learn even more about the telescope.

ALMA has revolutionized the field of planet formation, but also the field of astrochemistry. Actually, ALMA has become the astrochemist's best tool, allowing us to detect faint lines in regions we could not see before, such as protostars and protoplanetary disks. For example, we discovered the first complex molecule and made the first measurement of the ratio of nitrogen isotopes in a disk. After the famous HL Tau image appeared, I had the privilege to participate in the DSHARP project which revealed incredible dust substructures in disks. More recently, I was co-leader of the MAPS project, where we mapped the emission from tens of different molecules in disks.

ALMA will continue to make exciting discoveries, and I feel lucky to be in a position where I can make a contribution to the field of astrochemistry. This field is relatively new in Chile but now there are a few of us across the country. More importantly, since I became a faculty member at the Pontificia Universidad Católica, I have been given the chance to start training the younger generation in the field of astrochemistry and planet formation. My hope is that Chile will become a leader in these fields, and take advantage of the fantastic observatories we have in our country.

For all these reasons, ALMA means so much to me, not only because it gave me my career, but also on a personal level. I actually grew up very close to the ALMA site, in the city of Antofagasta. I moved to Santiago in 2004 to enroll in the Universidad de Chile, the same year that ALMA construction started. However, back then I never imagined I would become an astronomer and use this fantastic telescope that is now practically in what was once my backyard.

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High Angular Resolution Imaging – ALMA's performance exceeded the angular resolution defined in the third science goal by a factor of 10, achieving an angular resolution of 10 milli-arcseconds, or 0.010 arcseconds. This is equivalent to discerning a basketball hoop located about 9,000 km distant (the distance between Los Angeles and Munich, Germany), or even a common whale at the distance of the Moon. It is clear that this third science goal was critically important to obtaining the images of protoplanetary disks, but it applied equally to a broad range of astronomical studies. It was a breakthrough in high angular resolution imaging. Now, after nearly a decade of observing with ALMA, imaging with sub-arcsecond angular resolution has become rather commonplace. More than 650 projects in 4,000 have specified at least one aspect of their observing campaign to observe with greater detail than 0.1 arcseconds. That is, about one in six ALMA projects are aiming at this level of detail when imaging the sky.

The physical size of an object that appears to cover 0.1 arcsecond on the sky depends on the distance to that object from the telescope on Earth. At the distance of some of the nearest sites of star and planet formation, that distance equals about 10 times the distance of the Earth to the Sun, or 10 AU. An observation with better than 0.1 arcseconds resolution toward our neighbor galaxy, the Large Magellanic Cloud, would resolve details of about 5,000 AU. That is significantly larger than the size of our solar system, but much smaller than the size of the clouds where groups of stars are formed. Hence, one can begin to study the sites of planet formation within our Galactic neighborhood, and star formation beyond the limits of our own Galaxy. Even phenomena in the seemingly distant universe, such as massive, energetic jets launched from active galactic nuclei of galaxies born millions of years ago, can be studied in detail.

In order to have an idea of what it takes to obtain this angular resolution goal, it is helpful to revisit the different array configurations available at ALMA. The ALMA antennas can be rearranged in a variety of positions, and the farthest distance between any two antennas determines the smallest level of detail that can be observed. Depending on the exact wavelength being observed, 0.1 arcsecond resolution can be obtained with the configuration whose longest baseline is almost 800 m, or half a mile. If observing with a longer wavelength, then the antennas would have to be spread even farther, possibly up to about 8 km in order to detect such small structures. Nonetheless, ALMA was designed to operate with its antennas separated by up to 16 km, which is to say that the goal of observing with 0.1 arcsecond resolution is well within its design reach, as long as the additional "precision" requirements are also met.

Long baselines are not enough to meet the "precision" aspect of the third science goal. It is worth delving into the meaning of "precise." For astronomical imaging with ALMA, this was (precisely) specified: "*Here the term precise image means representing within the noise level the sky brightness at all points where the brightness is greater than 0.1 percent of the peak image brightness. This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees.*" In other words, synthesizing the three science goals, it was imperative not only to see objects that were relatively small and very distant, but also to distinguish a vast array of subtle differences in source structures and the different combinations of gas and dust that reside therein. The study of minute features in distant objects depends on corrections of signal fluctuations due to instrumental and atmospheric effects in order to reach what's known as a high "dynamic range" image. With very careful signal processing, the goal is to detect the two extremes of faint and bright light in the same observation – for example, a booming central emitting region of an object, as well as the faint outer limits. The complete picture is critical to a deeper understanding of complex astronomical targets.

The result of such stringent constraints on antenna configurations and imaging capacity is stunning pictures of astronomical objects in unprecedented detail. Astronomers began showing detailed color-scale ALMA images at conferences and in their publications, rather than the contour plots, spectra, or other less eye-catching data representations they had used when observing with previous arrays. In the early years of ALMA observations, conference presentations regularly included a "then" and "now" view of a certain astronomical object under study, emphasizing how much more detail could be seen in the new view with ALMA. Speakers would use phrases like, "*And that observation was made in less than an hour of observations with ALMA,*" or "*That was done in less than half the time of previous observations,*" emphasizing the impressive power of ALMA to observe great detail within a reasonable amount of time.

The Breadth of ALMA Science

In the approximately 10 years since ALMA operations began, scientific teams worldwide have dreamt, planned, executed, and analyzed observations addressing the variety of scientific topics incorporated into the ALMA design concept. From cosmology to neighboring galaxies to our own Milky Way galaxy and the stars, planets, and other astronomical bodies within, here in Figure 10.3 we provide a snapshot of some of the impactful discoveries in ALMA's first 10 years of operations.

ALMA's First Image – With just 12 antennas working together on the Chajnantor Plateau, ALMA observed the Antennae, a pair of colliding galaxies, and the result became the first scientific image from ALMA to be released on 3 October 2011. This is just one example of a new view of the Universe, beyond what had previously been studied with visible and infrared telescopes at similar resolution, or with radio telescopes at lower resolution. The galaxies in the Antennae began colliding relatively recently, only a few hundred million years ago, making it one of the youngest known major galaxy mergers. As such, at a distance of about 70 million light years, telescopes can discern the two remaining nuclei from the original galaxies, dusty filamentary lanes that connect these

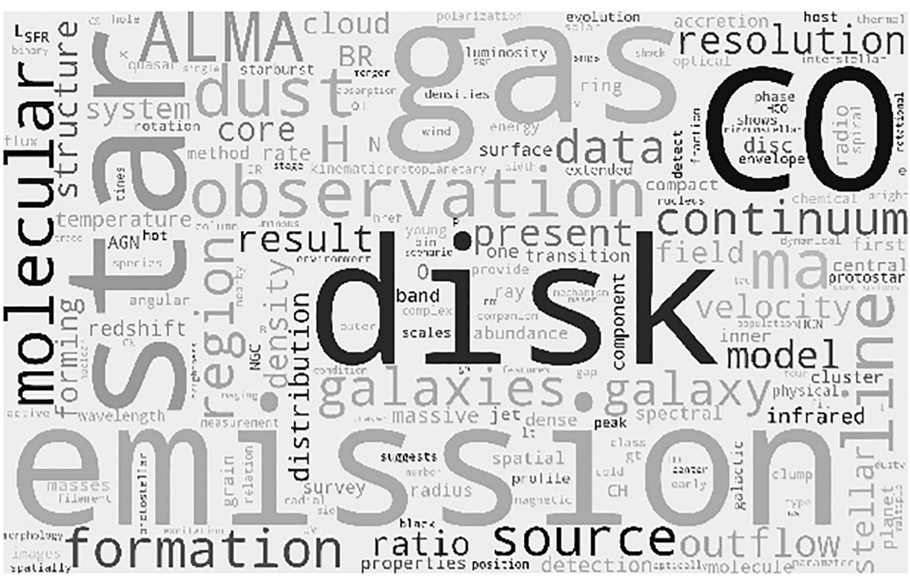

Figure 10.3 A word cloud representing the abstracts of publications using ALMA data as of September 2022. Very roughly, the size of the word corresponds to its frequency in the text of the publication abstracts, summaries of the work. The image gives a visual impression of the topics that dominate ALMA science programs. Credit: Courtesy of Felix Stoehr, reproduced by permission.

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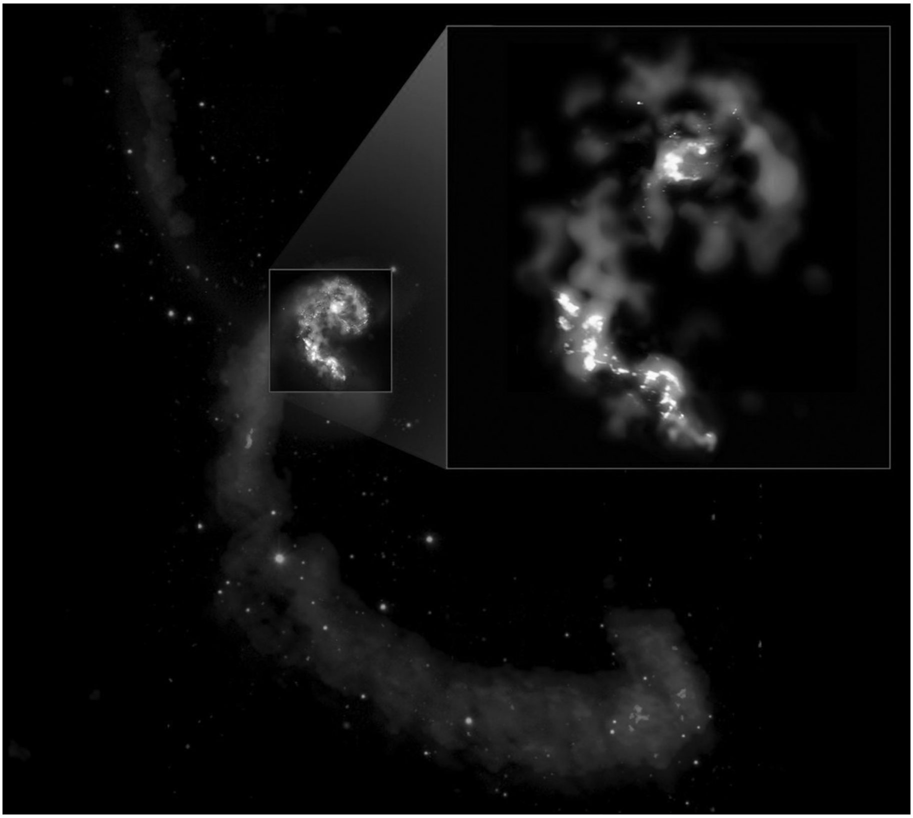

Figure 10.4 The first scientific image with ALMA, of the two interacting galaxies that form the Antennae. The image is a composite of CO emission from ALMA, H I emission from the VLA, and optical/infrared emission from HST and CTIO. Credit: ALMA/ESO/AUI/NINS, CC BY 4.0; HST/NASA/ESA, CC BY 3.0; J. Hibbard; NRAO/AUI/NSF, CC BY 3.0; NOAO/AURA/NSF, CC BY 4.0.

nuclei, and star clusters scattered throughout. ALMA observed the dust and the carbon monoxide gas that emit millimeter-wavelength light in the Antennae galaxies, and soon thereafter the Observatory produced its first image, shown in Figure 10.4, to celebrate ALMA's first science result. The ALMA data were obtained as part of the Science Verification campaign, and they were compared with similar observations from other millimeter wavelength arrays to corroborate ALMA's first observing modes.

It was a Chilean graduate student, Cinthya Herrera, who published the first peer-reviewed journal article with ALMA observations while completing her doctorate degree in Paris, France.[7] In the paper, she and her co-authors combined ALMA data of the Antennae with observations they had made with the VLT, an

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optical facility also in the Atacama Desert, about 300 miles away from ALMA. This allowed them to compare the carbon monoxide and molecular hydrogen gas, both important components in the structures that form stars.

It is worth reiterating here that carbon monoxide is one of the main design drivers and likely the most commonly observed molecule with ALMA, as it allows astronomers to peer into the otherwise invisible hydrogen clouds, which are the sites where stars form. In fact, carbon monoxide is targeted in the observing setup of about one-third of projects that were observed with ALMA to date. This has been the “workhorse” molecule for ALMA since inception. Whereas the study of CO began with single-dish telescopes, ALMA was honing in on greater detail in the morphology and kinematic structure of CO gas reservoirs throughout the Universe. The first detection of CO gas around a young exoplanet orbiting a star about 400 light years away came in 2022, when Jaehan Bae[8] found this small but important detail in the data that were part of the ALMA Large Program known as MAPS. Astronomers had expanded upon the goal to detect gas structures around stars and were endeavoring to study the gas that goes on to specifically form planets in those systems.

Astrochemistry – Going beyond CO, astronomers have used ALMA to study the universe as a chemistry lab, searching for molecules much more complex than carbon monoxide. Primarily, the search is on for increasingly complex carbon-based molecules, as these are considered the basic building blocks of life. If the conditions are right, simple molecules like CO, hydrogen, and water can go on to form amino acids and proteins, which are notably important to human biology and life in the Universe. Astronomers search for environments reminiscent of what are likely the precursors to planetary systems that could host Earth-like planets. One extremely young star with characteristics to suggest that it will go on to become a star similar to our Sun is known as IRAS 16293-2422, located at a distance of about 400 light years in the constellation Ophiuchus. It has been studied extensively with ALMA[9] since first being observed in 2012, and it was found to include the simple sugar glycolaldehyde, as well as methyl isocyanate, which is lethal but can form peptides and amino acids by combining with other molecules in interstellar environments. Figure 10.5 shows the spectrum of one of eight star-forming clouds in the galaxy NGC 253, about 25,000 times farther away than IRAS 16293-2422. A total of nineteen molecular species were identified in this cloud. Detections of complex molecules like these inspire theories of how life as we know it may have begun throughout the nearby Universe.

ALMA does not only look at stars similar to the Sun, but also the Sun itself. Teams have proposed solar observations since 2016, and data were released to the astronomical community in 2017 as part of the Scientific Verification

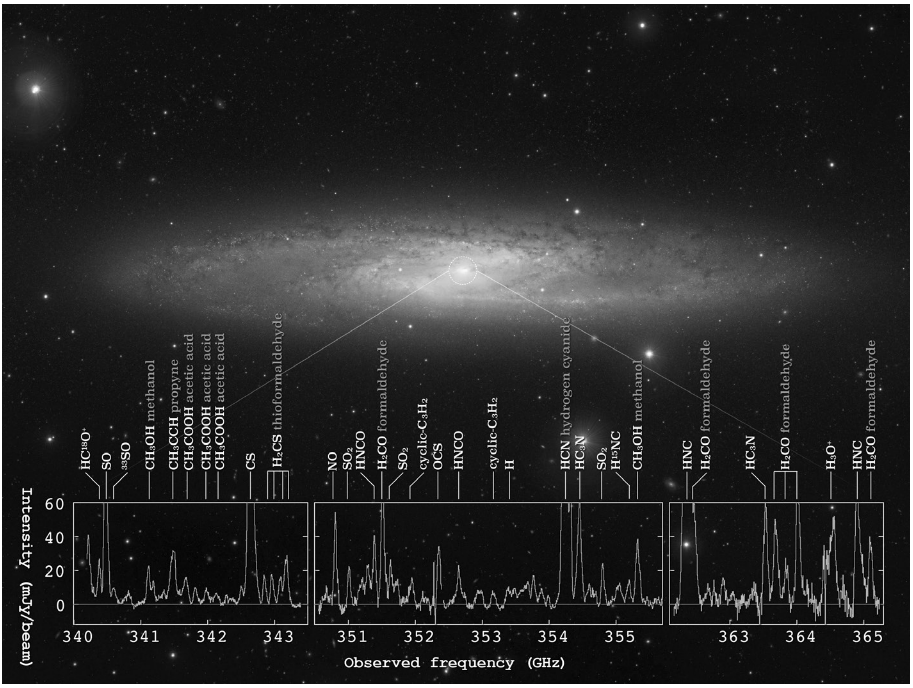

Figure 10.5 The spectrum of molecular emission lines detected in the heart of the star-burst galaxy NGC 253. Credit: J. Emerson; ESO, CC BY 4.0; ALMA/ESO/AUI/NINS, CC BY 4.0; adapted from Ando et al. (2017); ©AAS, reproduced by permission.

process[10] to demonstrate ALMA's capabilities in this area. ALMA is able to probe the solar chromosphere, and it is important, especially for determining the temperature of the chromosphere in high detail. The chromosphere is one layer of the Sun's atmosphere, lying between the photosphere below and the corona above; the chromosphere is likely important in transferring heat from the solar interior to the outermost layer, the corona. The ALMA observations are often analyzed in concert with data from other telescopes that record other wavelengths of light, including NASA's Solar Dynamics Observatory and the Interface Region Imaging Spectrograph. Interest among an international cohort of solar researchers can be summarized in the statement by Maria Loukitcheva who has been studying millimeter waves from the Sun for over two decades[11]: "*The importance of ALMA for solar physics is indisputable.*" Sven Wedemeyer, a professor at the University of Oslo who leads several major research initiatives to observe the Sun with ALMA, reinforced the importance but also the challenge, stating: "*Interferometric observations of a dynamic source like the Sun and the reliable reconstruction of corresponding image series are challenging tasks.*" The observed imprints of magnetic loops and variations in temperature over time are important phenomena to better understand the solar composition.

Distant Galaxies – ALMA has been on the hunt to detect the most distant galaxy, as it would appear when it was very young, formed early on in the history of the universe. Astronomers use observations of distant galaxies as "time machines" in order to understand the conditions of the universe at an earlier time. One galaxy, named SPT0418-47, was observed by ALMA and established as the most distant then known Milky Way look-alike. What was remarkable about this galaxy, about 12 billion light years away, was how unremarkable it looked even though it was formed when the Universe was just 1.4 billion years old. The results published by Francesca Rizzo,[12] at the time a graduate student at the Max Planck Institut für Astrophysik in Germany, showed that it has two features in common with our Milky Way – a bulge and a rotating disk. The galaxy appears surprisingly unchaotic, even though it was previously expected that galaxies in the early universe should be turbulent and unstable, eventually becoming more orderly with time. The observations of SPT0418-47 utilized a clever technique and an effect known as gravitational lensing, effectively converting a nearby galaxy into a powerful magnifying glass that allows ALMA to see unprecedented details of objects in the more distant universe. In this case, the intense gravitational pull of a galaxy between ALMA on Earth and SPT0418-47 focused the light of the distant galaxy, and as a result, SPT0418-47 appeared magnified as a near perfect ring of light around the nearby lensing galaxy. A model of the lensing allowed the team of astronomers to reconstruct the galaxy's true shape, which turned out to have a galactic disk that was much more orderly than any other known distant galaxy.

Less than one year later, astronomers published a study of another galaxy BRI 1335-0417,[13] whose mass is roughly equal to the Milky Way, and whose distance is similar to that of SPT0418-47. Takafumi Tsukui, a graduate student at the Graduate University for Advanced Studies (SOKENDAI) in Japan, led the study of an image they found in the ASA that revealed evidence of a spiral structure, in addition to the rotating disk and massive central region. The spiral structure was therefore the most distant such example known at the time, and Tsukui expressed his excitement saying "*The quality of the ALMA data was so good that I was able to see so much detail that I thought it was a nearby galaxy.*"

ALMA is not limited to studying galaxies like the Milky Way with notable spiral structures. Astronomers continuously search for faint signals, thanks to ALMA's high sensitivity, that are likely candidates for even more distant galaxies. To this end, ALMA observers found two galaxies that formed more than 13 billion years ago, less than 1 billion years after the Big Bang. The international team of astronomers had targeted forty very specific galaxies at "cosmic dawn" as part of an ongoing large program called Reionization-Era Bright Emission Line Survey (REBELS). The results[14] suggest that there may be more galaxies forming in early in the history of the Universe than expected.

Competition for Observing Time

ALMA's scientific payoff is clear from the published results, but it is worth elaborating on the observing process. ALMA is truly a community-driven, publicly funded, and internationally run facility. How does one make ALMA observations, in practice? Next, we explain the process from idea to observation to discovery to publication of scientific results.

Open Skies – ALMA was designed for a breadth of scientific topics, beyond the specific examples we just discussed. ALMA scientific categories include, among others, cosmology and the high redshift Universe, galaxies and galactic nuclei, interstellar medium, star formation, astrochemistry, circumstellar disks, exoplanets, the solar system, stellar evolution, and the Sun. Anyone in the world can propose an observation with ALMA, at no cost to the proposer. According to the Trilateral ALMA Agreement, the time allocated for observation with ALMA should, over the long term, adhere to the relative level of funding of the respective regions, resulting in 33.75 percent for the North American partners, 33.75 percent for ESO member states, and 22.5 percent for the East Asia. Taiwan is a unique case whose observing time can be tallied as North American or East Asian, according to their agreements with both regional members. Additionally, 10 percent of time is allocated for Chilean proposals, in exchange for their role as host of the telescope. Finally, proposals can be submitted by astronomers outside of the previously mentioned regions and alliances. Such "open skies" time is divided among the partners according to their respective shares for up to five percent of ALMA's observing time, and beyond that threshold, it is charged to the North American share.[15]

In addition to the annual call for proposals, up to five percent of the observing time in a Cycle can be allocated by the ALMA Director as Director's Discretionary Time. These proposals are generally cutting-edge science, typically those for which immediate observations are needed to capture an unanticipated short-lived astronomical event or science cases that have the potential to lead to a breakthrough discovery. In some cases, the proposed observations may be rather risky, but could have a large impact from only a small amount of observing time.

Scientific assessments by reviewers (detailed in following sections) form the foundation for what is known as a "scheduling exercise" to determine which top ranked proposals could realistically be executed in the upcoming year. Final grades of A (top priority), B, C, and U (unscheduled) are assigned to each proposal, and proposal authors are also notified of the "quartile" within which the proposal ranked. The scientific ranking is not the only determinant of whether a proposal is eventually scheduled, because other factors such as regional balance and scheduling feasibility have to be taken into account.

Annual Observing Cycles – As construction progressed, astronomers worldwide knew that ALMA was coming, and would open up a window to astronomical details they had never seen before, thanks to the combination of ALMA's angular resolution and sensitivity. The first call for proposals was opened in 2011, for what was known as "Cycle 0." Cycle 0 would span 9 months and offer 500–700 hours of time on a somewhat limited array. This period was known as "Early Science," and the observing time came with the risks that accompany early operation of a telescope. Nonetheless, astronomers eagerly applied to use ALMA for their proposed scientific endeavors, since ALMA, though incomplete, was already more powerful than other interferometers that observed at the same wavelengths. Although its formal inauguration would be in 2013, the revolution with ALMA had begun. The "Early Science" period included Cycles 0–2, with each cycle lasting between 9 and 17 months. With the call for Cycle 3 in 2015, ALMA entered into a phase dominated by scientific observations, but still balanced with engineering, maintenance, and development activities. From then on, the cycles lasted twelve months each, following a cadence such that the call for proposals closed in April of each year, for observations to be scheduled between 1 October of the same year, and 30 September of the following year.

With each cycle, more capabilities were offered, notably more antennas, more receiver bands, and more available observing time. The available observing time eventually reached 4,300 hours (about half the hours in a year) on the 12 m array in Cycle 7, which was a requirement for full operations, and remained at that level as of the writing of this book. Additionally, Cycle 7 offered a "Supplemental Call" due October 2019, in order to add additional projects to the queue, specifically those that could be observed with the ACA during undersubscribed allocations of the observing queue. The main call that year offered 3,000 hours of time each for the ACA, also known as the Morita Array, and Total Power Array. A supplemental call would also be offered in 2021. A smaller one had been offered in Cycle 4, but none are planned for future cycles. At the time of the writing of this book, the most proposals submitted for any single cycle were 1,836 in Cycle 6, steadying between 1,700 and 1,800 for Cycles 7–9. It is worth noting that considering the time requested, ALMA maintains an over-subscription rate of around six, varying somewhat by

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region and cycle. In other words, for every proposal accepted to be scheduled in the coming year, about five are rejected or unlikely to be observed.

Proposal Preparation – ALMA was designed such that non-experts in millimeter wave interferometry would have the opportunity to pose scientific questions and undertake the corresponding observations. Around the time of the annual call for proposals, community workshops are organized by the ALMA Regional Centers (ARCs), with ALMA staff available to assist astronomers from their region with proposal preparation. In the case of the North American ARC, the ALMA Ambassadors program trains postdocs and graduate students from institutions in North America and Chile, in order for them to subsequently host workshops for their local astronomy communities.

In order to apply for ALMA time, astronomers must prepare a four-page document detailing the scientific justification for the observations; two additional pages are allocated for the largest subset of programs, which also require a team management plan. Additionally, some predefined details of the observational setup must be entered into a software interface known as the Observing Tool. There, the astronomers indicate the coordinates for their observation(s), frequencies to tune the receivers, and required level of detail needed for a detection. The Observing Tool will calculate the amount of time needed to accomplish the goals based on the technical setup. In early cycles, with limited time available, observations shorter than a few hours were encouraged, but with subsequent cycles that time recommendation has been lifted. Astronomers now request the amount of time necessary to accomplish their scientific goals, measured in terms of observing sensitivity to ensure detection of their designated source(s). Moreover, by 2020 advisory committees were encouraging proposals with larger time requests, broader in scope. By Cycle 9, the median request for observing time with the 12 m array was 12.2 hours per project.

Panel Review – Reviews of proposals by panels of experts are common in astronomy and other scientific fields as a mechanism for selecting the most compelling scientific pursuits in a given area for a given period of time. ALMA followed suit for at least Cycles 0–9, for all or a subset of proposals. The panelists were selected for being experts in the field of millimeter interferometry and the scientific topics being studied by ALMA. In addition to expertise, the panelists reflected the regional balance of ALMA. Approximately two-thirds of the panelists were, in equal parts, North American and European, complemented by colleagues from East Asian institutions, and about 10 percent from Chilean institutions. To combat potential biases, intentional efforts ensured gender balance among the panelists as well.

Panels were organized according to scientific category, with the number of panels proportional to the number of proposals received in a given category. The number of panels had to gradually increase to keep up with the growing number of submitted proposals per cycle until leveling off at around 1,800 proposals, in an effort to keep the number of proposals reviewed by a given panelist within a reasonable range. At its peak, panelists of certain expertise categories sometimes read more than 100 proposals, and up to 158 panelists were recruited for a given cycle. Panelists generally committed to serving three cycles before rotating off. It became a badge of honor to be invited, and the panelists often celebrated at a culminating banquet in which they were honored for their service.

Distributed Peer Review – Although panel reviews had been the standard for telescope time allocation at ALMA and other observatories, ALMA instituted an alternative known as distributed peer review, in the hope that it would distribute the burden of the process more equitably. In a distributed peer review process, someone who submits a proposal agrees to be responsible for reviewing a fixed number of proposals among the collection of submitted proposals. The same individuals submitting proposals are also contributing to selecting the best proposals to be observed.

The first implementation of the distributed variant at ALMA was for the Supplemental Call of Cycle 7, in which observations using the ACA could be proposed before 1 October 2019. Several hundred proposals were received in this call, with an equal number of "designated reviewers"[16] participating in the first distributed peer review of its size for astronomy. Thousands of reviews were therefore processed, 10 for each submitted proposal.

Following success in the Cycle 7 Supplemental Call, ALMA decided to ratchet up the magnitude of the distributed process. In the call for proposals of Cycle 8, held in 2021, only the proposals requesting more than 25 hours on the 12 m array or 150 hours on the 7 m array – so-called medium to large proposals – were evaluated via the usual peer review process. In contrast, 1,497 proposals were processed through the distributed panel review process, followed by 1,729 proposals in Cycle 9, the most for any telescope review of its kind to date.[17] These were the first instances in which the majority of observing time at a major astronomical facility had been allocated this way, and an example of ALMA operating at the forefront of the field.

Dual Anonymous Review – Another important aspect of the ALMA observing procedure has been the aim to equitably allocate observations among the worldwide partnership. Following the described proposal review process, certain systematics became apparent in early cycles. There were indications that proposals with

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a male principal investigator fared better than those led by a female, North American and European proposals were scored higher than those written by authors in East Asia or Chile, and astronomers' success seemed to be correlated with the number of times that they had previously submitted proposals for observations with ALMA, a so-called "prestige bias."

The proposal review process evolved with time, first making the panel reviewers aware of unconscious biases and hiding some author information in the proposal tools, then randomizing the order of authors' names in the cover page, and finally taking the leap to a fully dual anonymous procedure. Ultimately, the proposals had to be written such that the identities of the proposing teams were unknown to the reviewers, just as the reviewers' identities were unknown to the proposing teams at the time of the proposal call. The first fully anonymous ALMA proposal cycle took place in 2021, and by that time many of the major international telescope facilities had adopted this modality as well.

A thorough report investigated the impact that the dual anonymous process had on apparent systematics.[18] The prestige bias seems to have subsided, and PIs who submitted a proposal for the second time had ranks comparable to those most experienced PIs with many years of proposals under their belts. Interestingly, no significant differences of ranks based on gender were found, and the systematics of regional affiliation remained similar to prior cycles. Throughout, the ALMA project has placed high importance on equity and fairness in granting observing time, and the dual anonymous and distributed peer review components of the proposal process were steps in this direction that ALMA continues to monitor for optimal outcomes.

Steps in Remote Observing and Reduction of Data

Remote Observing – The actual process of observing with ALMA, as experienced by the astronomers who proposed the approved observations, is rather mundane in comparison with the heroic adventures of the groundbreaking astronomers who had scouted the ALMA site and embarked on the many negotiations to make ALMA a reality. Once a proposal is accepted for observation, the proposal is translated into an observing setup via the Observing Tool, with the assistance of staff members at the ARCs and the JAO. Staff known as contact scientists are assigned to each proposal, and act as a sort of customer service representative throughout the process. The proposal authors check to make sure all the details are as intended. Then the observations are put into a queue.

Queue observing is a mode by which the projects that meet certain criteria (weather, antenna configuration, orientation of the sky) during a given period are accordingly identified and able to be fit like puzzle pieces into the telescope agenda. Ultimately, observations are done by ALMA staff, rather than the astronomer(s) who proposed the observations. This is certainly an efficient, if perhaps anticlimactic way for the proposing team to obtain data. A team of one or more ALMA astronomers act as Astronomer(s) on Duty together with one or more telescope operators, usually engineers by training, at all times. The observations may be undertaken 24 hours per day, 365 days per year, although the facility is generally closed in February for maintenance and weather constraints, and time is shared throughout the weeks between science operations, engineering, and maintenance of the array. In order to maintain staffing levels, astronomers and operators serve on rotating 8–10-hour shifts throughout the day (and night), with a shift usually lasting a total of 8 days at a time.

The astronomers running the observations at the ALMA site are about 30 km removed from the plateau where the signal meets the ALMA antennas. This is because the astronomers, and other staff, work from the Operations Support Facility (OSF) during their shifts, located at the elevation of 2,900 m above sea level, compared to the more than 5,000 m elevation of the AOS facility at the Chajnantor Plateau where the antennas are situated.[19] The astronomers and telescope operators can control the antennas from the control room in the technical building at the OSF. A photograph of nightshift astronomers in the ALMA control room during early science observations is shown in Figure 10.6. The observed astronomical signal passes through a fiber optic cable buried underground from the AOS to the OSF, on its way to Santiago and around the world.

Since late 2019, ALMA engineers and astronomers have developed the tools to enable operating the antenna array from an even greater distance, via the control room extension at the ALMA Santiago Central Office (SCO). In other words, astronomers can run observations from over 1,600 km away from the antennas themselves. While indeed this was a very convenient and critical feature during certain periods of the COVID-19 pandemic, the control room extension had already been in planning phases since mid-2019, with the expectation that it will endure even as COVID-related travel restrictions and safety protocols were lifted. The control room extension ensures accessibility, flexibility, and reliability for the observing process while reducing the travel budget implied by the previous mode of operations. While some staff will inevitably always need to travel to the antenna site, it is no longer necessary for all staff to travel for every shift.

Data Reduction – Once the data come off the telescope, and follow their fiber optic path to Santiago, they are still not ready for scientific investigation. The JAO, together with the ARCs, has taken responsibility for the next stage of data quality assurance and reduction.[20] The quality assurance ensures that the

Figure 10.6 Nightshift in the ALMA Control Room during early science. Left to right: (standing) Rainer Mauersberger (ESO), Robert Lucas (ESO), Alison Peck (US, Deputy Project Scientist), Mareki Honma (Japan); (seated) Adele Plunkett (US); Manuel Aravena (Chile). Credit: Max Alexander; ESO, CC BY 4.0.

data meet the specifications set forth by the project's Principal Investigator. The data processing and reduction is performed via software known as the ALMA Science Pipeline, often but not always without human intervention. In the process, signals are calibrated and reference images of the target and calibration sources are generated. The principal investigator will receive the raw data and some or all requested images, along with access to the calibrated data, in order to begin their scientific analysis, or to perform more specific and nuanced data processing.

ALMA Science Archive – Data are available to the astronomical community via the ASA, accessible via a webpage. Behind the web interface is a database that stores all of the data, together with information about the observations that generated these data. The Principal Investigator (PI) will initially access their requested data via the ASA, following a specified link or by logging into the system and navigating the search and download functions. ALMA adopted a proprietary period of one year for most projects, meaning that datasets are exclusively reserved to the proposing team for the first twelve months after the data are released to the PI, that is, after quality assessment and pipeline reduction. The PI may delegate

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other users to access the data. Anyone can learn of the existence of specific data from the time that they are made available to the PI, with the data having been ingested into the archive database, and the date on which the data will be made public is readily apparent. Beginning at one year after the time of data release, the data are completely public, and accessible to anyone, consistent with NSF's Open Skies policy and the general sentiment that astronomical observations belong to everyone.

Archival data have been shown[21] to reinforce the legacy value of a telescope project, with the impact increasing with time as the archive grows in size, in terms of number of datasets and size of the data. ALMA tracks how many published studies incorporate data that were requested by one of the authors of a given study, as well as studies in which teams used data only accessible via the public archive. About a quarter of the publications based on ALMA data use at least some archival data. By late 2019, the ASA already hosted more than 1 PB (peta-Byte, or one thousand tera-Bytes) of data.

Publication Statistics

The impact, breadth, and depth of astronomical observations are not trivial to quantify. The main numerical assessment of how prolific a telescope facility has become is the number of scientific publications (peer-reviewed journal articles) that utilize the data from that facility over time. Figure 10.7 shows how the number of ALMA publications has grown since the first early science observing, amounting to over 400 publications per year – more than one per day – after a little less than 10 years of observations.

ALMA is an international project designed to serve the world astronomical community. Figure 10.8 shows the diverse countries to which authors of ALMA research articles are affiliated; more than three dozen countries are represented among authors.

Large Programs

According to ALMA documentation,[22] Large Programs are a subset of observations that "*should address strategic scientific issues that will lead to a major advance or breakthrough in the field.*" Large Programs are those requesting observing time greater than a defined threshold – currently more than 50 hours with the 12 m array or 150 hours with the ACA. Observatories often allocate some fraction of their observing time to this kind of project, seeking results not feasible with one or more smaller projects. Large Programs were first advertised and accepted in 2016, with ASPECS and DSHARP forming the first class.

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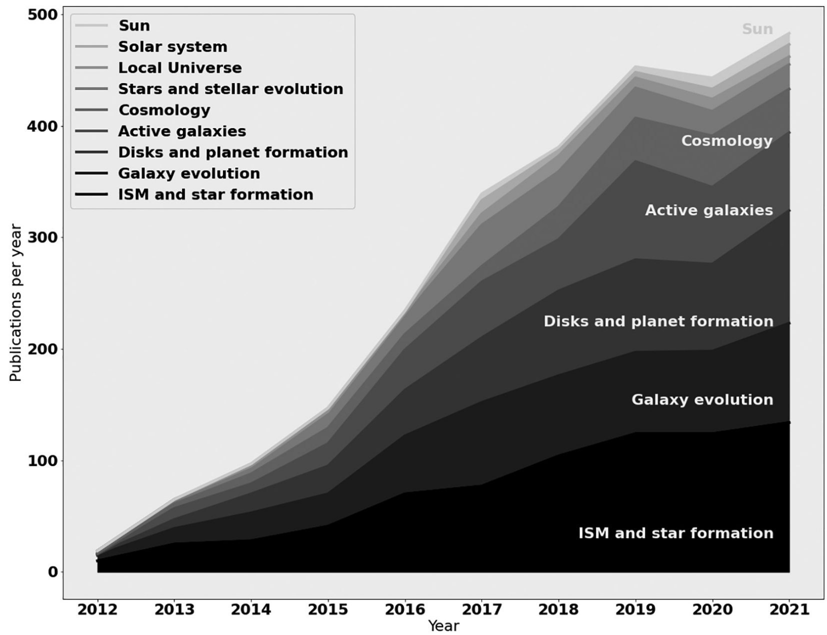

Figure 10.7 Publications in refereed peer-reviewed journals in the first 10 years of ALMA operations, according to topic. Courtesy of F. Stoehr, reproduced by permission.

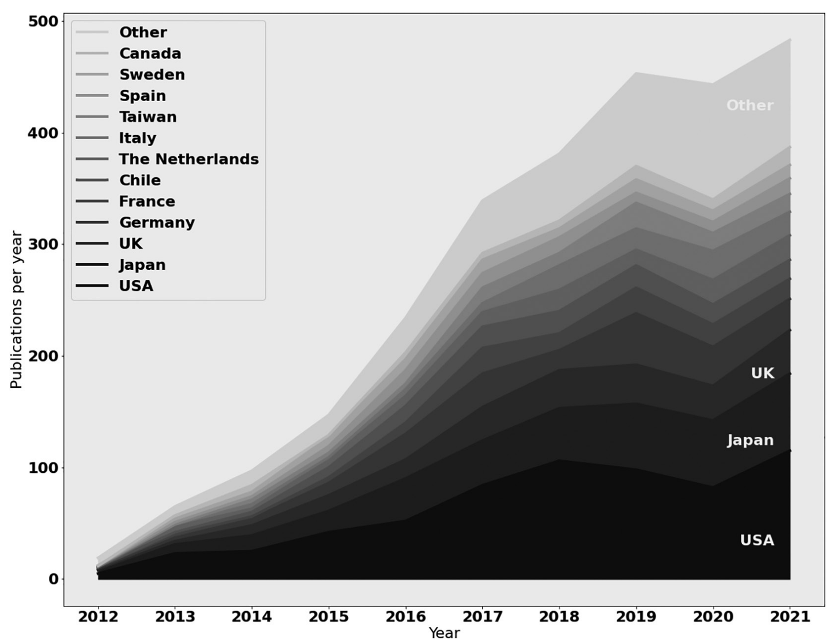

Figure 10.8 The national affiliations of the first authors of publications using ALMA data, during the first 10 years of ALMA operations. The “other” category includes at least two dozen countries. 2,661 publications were reported through the end of 2021. Courtesy of F. Stoehr, reproduced by permission.

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A unique aspect of the Large Programs that sets them apart from the other observations is that the team commits to providing high-level data products, free and publicly available, generally via a webpage. These data products are somewhat loosely defined, since the individual programs will naturally necessitate different types of analysis, depending on their scientific objectives. Some examples of the data products are the images that have been generated using different specifications to bring out different levels of detail, along with the scripts used to generate the images. Other examples of data product contributions include spectral energy distributions of observed sources, emission radial profiles, spectra, and source catalogs, among others. The intention is to facilitate sharing of data that enables follow-up or complementary science based on the same observations. These will ensure additional legacy value for the programs, as the astronomical community can access these data products for follow-up studies and analyses.

Very Long Baseline Interferometry

A particularly newsworthy result from a network of telescopes around the world, including ALMA, was the first image of a black hole. A series of six papers[23] were published in a special issue of *The Astrophysical Journal Letters* in 2019 to announce the breakthrough, and reveal the image of the black hole at the center of the galaxy Messier 87, in the cluster of galaxies known as Virgo.

ALMA was certainly not alone in this discovery. Instead, it contributed data along with seven other telescopes: the Atacama Pathfinder Experiment (APEX) in Chile, the IRAM 30 Meter Telescope in Spain, the JCMT in Hawaii, the LMT in Mexico, the SMA in Hawaii, the SMT in Arizona, and the South Pole Telescope. These facilities formed the Event Horizon Telescope (EHT), an Earth-sized interferometer that uses the technique known as Very Long Baseline Interferometry (VLBI). VLBI allows the EHT to achieve an angular resolution of 20 micro-arcseconds, enough to read a newspaper in New York from a sidewalk café in Paris. The EHT team detected light at a wavelength of 1.3 mm and provided direct visual evidence of a supermassive black hole by imaging its shadow, shown in Figure 10.9. Particularly noteworthy, technically speaking, is the additional sensitivity and baselines provided by the Chilean facilities ALMA and APEX, in order to recover the clearly ring-like structure in the image.

Since then, the origin of the jet emerging from the Centaurus A black hole[24] has been imaged with the EHT, and, equally exciting, the detection of polarized light from M87 in 2021. One of the primary goals of EHT was to obtain an image of Sagittarius A* (Sgr A*, pronounced “A-star”), the supermassive black hole at the center of our own Milky Way galaxy. On 12 May 2022, the EHT team presented the image of the Sgr A* black hole that they had obtained. This image

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was challenging to capture because the black hole spins so rapidly. The EHT Collaboration has been awarded numerous accolades, among them the 2020 Einstein Medal and the 2020 Breakthrough Prize in Fundamental Physics.

Future Prospects

Because technology advances rapidly, ALMA was designed with development in mind. The goal is to keep ALMA at the state-of-the-art for decades to come. Scientific research often leads to more questions than answers. In the case of telescopes, the most advanced technology enables observations that are deeper and more efficient, enabling new discoveries. These additional capabilities are facilitated through the ALMA Development Program, supported by the ALMA partners in addition to the funds they allocate for the annual operation budget. The principles of the development program were restated by the ALMA Board most recently at their 22 April 2020 meeting.[25]

The development program includes two categories: *studies* and *projects.* Studies, being smaller in scope, are administered by the different regions separately. They generally explore concepts that may lead to larger-scale longer-term developments that may be of interest to ALMA. Projects are larger-scale initiatives that provide specific deliverables, either hardware or software, for incorporation into ALMA.

The regions have adopted different strategies and frameworks for encouraging and supporting their development programs.[26] East Asia (EA) solicits

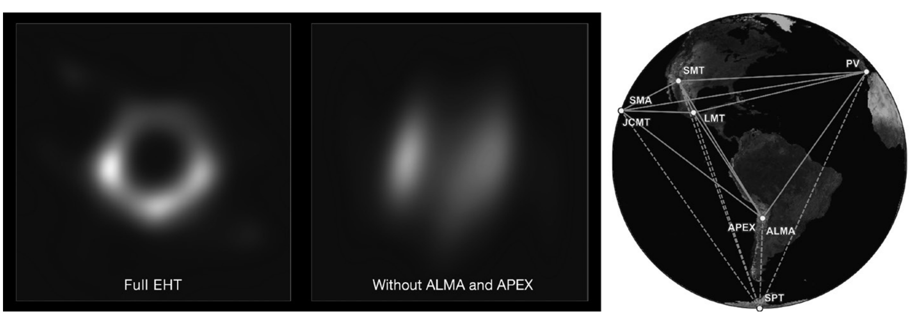

Figure 10.9 Images of the M87 black hole taken with the Event Horizon Telescope. Left: The image from the full EHT array, including data from two telescopes in Chile, APEX and ALMA. ALMA's large collecting area in the Southern Hemisphere added a number of baselines with high sensitivity. Center: How the image would look without the data from the telescopes in Chile. Right: The distribution of telescopes around the globe that contributed to the image. Credit: (left, center) EHT Collaboration; (right) Akiyama et al. (2019); CC BY 3.0.

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community feedback at annual EA development workshops, as well as from the East Asia Science Advisory Committee. NAOJ subsequently collaborates with its partner institutes in Taiwan (ASIAA) and Korea (KASI) to lead the development activities. Notable outcomes of the EA development projects are the Band 1 receivers, and the spectrometer for the Total Power Array of the Atacama Compact Array.

The European development program is administered by ESO, which works with ESO member states to solicit and approve about 5–10 studies on three-year cycles. A workshop is generally organized around the time of the call for proposals for development studies. Development programs led by ESO include Integrated Alarm System software for use by the ALMA telescope operators; and an initiative known as Additional Representative Images for Legacy (ARI-L), which reprocesses data products from early ALMA cycles, for ingestion into the ASA. Additionally, the Band 2 receivers were a European development program, with contributions from institutes worldwide, including many across Europe, Japan, Chile, and the United States.

Since 2011 and until the time this book was written, nearly fifty study proposals and a dozen project proposals from the North American community have been primarily funded by the development program in NA. The call for proposals of studies is issued annually, and funding can be requested up to about $250,000, to be used in a timeframe of one year. For the NA call, an independent panel is convened with consent of the NSF, and then an approved ranked list of proposals is incorporated into a recommendation to the NA executive, which has funding authority and responsibility for executing the studies' plans. Several notable development projects led by North American community members include the outfitting of antennas with equipment needed to enable ALMA to become part of the EHT, and several receiver developments, including an upgrade of Band 6, as well as a next generation correlator design. Software tool developments have also been made possible by North American development projects, including the ALMA Data Mining Toolkit (ADMiT) and the Cube Analysis and Rendering Tool for Astronomy (CARTA) used for data visualization.

ALMA2030 is the vision of the ALMA Observatory for the decade of the 2030s. The authors of the ALMA Development Roadmap[27] expressed the community sentiment by stating, "*The three level-one science goals of the ALMA baseline project have been essentially achieved in the first five years of ALMA operations*." The time had come to propose three new fundamental science goals to explore in the coming decade, and they were laid out with the common theme of origins – of galaxies, chemical complexity, and planets. While publications and the ASA contain hints and tantalizing evidence about these themes, astronomers will need additional capabilities from ALMA in order to search for more conclusive answers. Areas of study

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include detecting key elements in the first galaxies, tracing organic molecular formation throughout star and planet formation, and ultimately imaging regions where young Earths likely form and where origins of new life are probable.

The top priorities for the 2030 decade are new receivers capable of operating over broader bandwidths, along with an upgrade of the associated electronics, and the ability to process much more data. Additionally, facilitating more efficient data mining of the ALMA archive will lead to greater scientific return. Specifically, the Development Roadmap mentioned the following possibilities: extended baselines by factors of 2 to 3, in order to image nearby terrestrial planet-forming zones; faster wide-field mapping capabilities; increase the number of 12 m antennas; and incorporate a large single dish submillimeter telescope with at least a 25 m diameter. The latter option would enable deep, multi-wavelength images of the sky.

An international partnership is working to design, build, and install a new ALMA correlator, in a project called the Wideband Sensitivity Upgrade (WSU), with the aim of increasing the bandwidth and sensitivity needed by all three science goals of the Development Roadmap. The WSU aims to more than double the bandwidth of the system, meaning that at least twice as much signal information can be recorded in the same amount of time. Also, the spectral resolution, or the fine tuning of the system needed to identify specific molecular emission lines, will be enhanced. Until now, astronomers can be forced to choose between high spectral resolution or broadband recording; the new system should allow the best of both simultaneously.

Conclusion

The journey from first ideas to the reality of ALMA was long and arduous. It stretched 31 years from Owen's suggestion in 1982 that NRAO should build a "millimeter VLA" to the inauguration of ALMA in 2013. From Booth's 1991 proposal to the SEST Users Committee to build a millimeter array in Chile and Ishiguro's 1987 plan for a millimeter array in Japan, there are comparable lengthy time spans. Many, possibly most, of ALMA's users today were barely even born when these initial concepts were set forth. The difficulty of the journey lay in the extensive scope of ALMA and the correspondingly sheer amount of work that was required: refining the scientific goals, designing components, testing prototypes, negotiating contracts and agreements, finding and acquiring a site, assembling the array, and establishing the science centers that would assist users in proposing projects and analyzing data. The work was not resented. Rather, the participants enjoyed and took satisfaction in their efforts, like mountain climbers scaling a peak, focused on a common goal.

The journey was replete with potential hazards. The world of astronomy is densely populated by committees. Observatories appoint committees to hear the wishes of their users and to review their operations. The funding agencies have committees to review and advise on their programs. Community-wide panels set out the priorities for the future. Special situations can arise that call for the appointment of *ad hoc* committees. The drumbeat of reviews was an enormous burden on ALMA, but one that was inevitable. The hazard in every review is the potential for a poor report. Ringing endorsements are necessary from the full array of stakeholders. Tepid enthusiasm will not do. The stakes vary in their consequences. They can be less critical for internal committees but life and death for a review prompted by a crisis. The cost overrun that led to a total reset for the ALMA budget is an example of the latter. ALMA was saved after that review by the commitment to the common goal of transformational science at NSF and ESO.

Circumstances played a role in the success of ALMA, initial disappointments leading to opportunity. The failure of the 25 Meter Telescope project led to a focus in the United States on interferometry and the MMA. The NSF did not immediately fund the MMA, despite outstanding reviews. Had it done so, the United States would now have an array on an inferior site, inadequate to address today's scientific questions. The threat to SEST operations at ESO sparked the drive for the LSA. The lucky detection of CO at $z = 2.3$ boosted the cause of the MMA and led to the LSA's huge collecting area. The timing of the merger of the MMA and LSA was ideal, bridging the budget gap between the VLT and ESO's next generation optical telescope. Only in retrospect do these examples and others show how truly fortunate ALMA was in avoiding dead ends and seizing opportunities.

ALMA triumphed over seemingly intractable problems and cultural differences, but the true triumph of ALMA lies in the scientific discoveries it has enabled. The image of the disk surrounding the young star HL Tauri made the entire journey seem worthwhile. One could almost hear the gasp of amazement and relief from astronomers around the world when the image was released. HL Tauri had long been studied via the infrared emission from its circumstellar disk. ALMA with its sensitivity from its huge collecting area and resolution from its long baselines revealed in stunning detail the structure of the disk – rings of emission from the dust in the disk were separated by gaps where planets were forming. It was the next step toward seeing planets as they form. The cost of building and operating ALMA was a concern of other observatories dependent on NSF funding. At a meeting of a US National Research Council panel, the director of a leading optical/infrared observatory said, "*If I had been shown this image [HL Tau] and told that I could have it for a billion dollars, I would have said – that's a bargain!*" Like the discovery of interstellar CO, the image of HL Tauri was transformational. In

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its more than 1,000 citations, it is notable that 83 are from PhD theses of young astronomers who have been influenced by this groundbreaking discovery.

ALMA's capabilities are applicable by design to a wide range of research areas, from the Sun to stars, the Galaxy, nearby and distant galaxies. ALMA has transformed the study of the chemistry of interstellar molecular clouds in the Milky Way Galaxy and other galaxies near and far. Observations with ALMA have shed light on solar phenomena, the formation of planets, and the evolution of galaxies in the early Universe. ALMA is a critical element in the EHT, a global-sized very long baseline interferometer. The large collecting area of ALMA has enabled the imaging of the super massive black hole in the galaxy M87 and the one in the center of our own Milky Way. At the time of the writing of this book, ALMA was producing about one scientific article per day based on new observations or those in the ALMA Archive. It would prove to be as productive as the Hubble Space Telescope. With its annual investments in improvements and if the plans for ALMA2030 are realized, ALMA will continue to provide its powerful radio wavelength view of the Universe for very many years. Were ALMA's promises fulfilled? The answer is a resounding YES!

Notes

1 *The ALMA Development Roadmap* can be found at: https://almaobservatory.org/wp-content/uploads/2018/07/20180712-alma-development-roadmap.pdf.

2 *A Science-Driven Vision for ALMA* in the 2030s (Brogan et al., 2019).

3 The primary paper and survey description for the ASPECS large program is by Walter et al. (2016), and the team's website, with additional publications, a multi-wavelength interactive view, and access to data can be found at: http://aspecs.danielaleitner.de/.

4 Walter to Vanden Bout, private communication.

5 Making an image of HL Tau was the aim of a high-resolution test project involving a team of scientists. The image and analysis were reported by the ALMA Partnership (Brogan et al. 2015).

6 The images were published in the first article of the Astrophysical Journal Letters focus issue (Andrews et al., 2018). Images are also available in the data release: https://almascience.eso.org/almadata/lp/DSHARP.

7 Herrera's graduate studies (Herrera et al., 2012) were supported by a grant through a partnership between Chile's CONICYT and France's CNRS. Diverse international collaborations not only funded the construction and operations of ALMA, but also the subsequent scientific research.

8 Bae et al. (2022) published *Molecules with ALMA at Planet-forming Scales (MAPS): A Circumplanetary Disk Candidate in Molecular-line Emission in the AS 209 Disk Show Affiliations*, a paper that incorporated data from the MAPS Large Program. Viviana Guzman, who provided a short perspective for this chapter, is a co-author and collaborator.

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9 The source IRAS 16293-2422 was originally observed with ALMA in Cycle 1, and the first results were published by Jorgensen et al. (2016) as part of the ALMA Protostellar Interferometric Line Survey (PILS). The same campaign led to at least 29 publications as of 2021. See also Martín-Doménech et al. (2017) and Ligterink et al. (2017).

10 First teams to publish the ALMA Science Verification observations of the Sun were: Bastian et al. (2017), Iwai et al. (2017), Loukitcheva et al. (2017), and Shimojo et al. (2017). All three ALMA partners are represented among the authors of these papers, which appear to have stemmed from coordinated, collaborative efforts. The science verification data are available at http://almascience.org/alma-data/science-verification.

11 Two important, explanatory papers related to Solar observations with ALMA came from Loukitcheva (2019) and Wedemeyer et al. (2020).

12 The research paper by Rizzo et al. (2020) was the result of an effort of seven researchers based in Germany and the Netherlands. Such joint efforts are typical of many ALMA projects.

13 Takafumi Tsukui and PhD supervisor Satoru Iguchi published their results in (Tsukui and Iguchi, 2021).

14 The discovery (Fudamoto et al., 2021) by Yoshinobu Fudamoto from Waseda University and NAOJ came when unexpected light emissions were detected from a region of space that was presumed to be empty and dark.

15 To date, such "open skies" proposals have not exceeded 5% of the total ALMA observing time for any given cycle. The excess time is to be allocated to the North American share, per current US government policy associated with funding from the National Science Foundation.

16 Each proposing team designates a reviewer from among their team. Also, a reviewer without a PhD has to indicate a "mentor."

17 A full overview is given by Donovan Meyer, J. et al. (2022).

18 Carpenter et al. (2022) give an overview and update on the ALMA proposal review process, with a focus on systematics between Cycles 0 and 8. They report some biases in earlier cycles related to the relative prominence of the Principal Investigator (PI), a so-called "prestige bias." The report does not report any findings of significant gender biases. They also looked at systematics related to regional affiliations of proposal authors.

19 A multi-disciplinary research team of experts from Canada, Switzerland, and Chile met at ALMA in April 2016 to examine observatory staff and study the effect of oxygen deficiency, a medical condition known as hypoxia, when working at high-altitude (Pun et al., 2018).

20 Data from the ALMA telescope needs to be processed before delivery to the respective astronomers. This is known as "data reduction." A software pipeline has been developed for this purpose, and the vast majority of data from the telescope pass through this pipeline processing. Data reduction tasks were initially distributed among the ARCs (Schnee et al., 2014), and in recent cycles, have been primarily the responsibility of a data reduction team at JAO. By Cycle 8, nearly 90% of data were processed at the JAO, compared with about 50% in Cycle 5, and in earlier cycles, the majority of data were processed at the ARCs. The ARCs complete the process with a final review and quality assessment before delivering data to the community.

21 See Peek (2017). www.scientificamerican.com/article/how-old-observations-are-building-hubbles-legacy/.

22 For a detailed description of Large Programs, see https://almascience/alma-data/lp.

23 The ALMA press release can be found at: www.almaobservatory.org/en/press-releases/astronomers-capture-first-image-of-a-black-hole/. The *Astrophysical Journal Letters* organized a special issue with the title "*Focus on the First Event Horizon Telescope (EHT) Results*," where Shep Doeleman, on behalf of the EHT Collaboration opened with *"We report the first image of a black hole."* The article proceeds to explain the ambitious observing campaign over the past decade, and the extensive coordination that led to the subsequent publications. After the first (Akiyama, K., et al., 2019) of six papers were published in 2019, two additional papers in 2021 expanded the study to the magnetic fields of M87. See, for example, Akiyama, K. et al. (2021).

24 Janssen et al. (2021) explain that the SMBH in Centaurus A bridges the gap in mass and accretion rate between that of Messier 87 and that of our Galactic Center.

25 *Principles of the ALMA Development Program* can be found at: https://science.nrao.edu/facilities/alma/science_sustainability/Principles_of_the_ALMA_Development_Program.pdf.

26 Summaries of the development programs of the three ALMA regions are given in *The ALMA Development Program: Roadmap to 2030* by Carpenter, J. et al. It can be found at: https://science.nrao.edu/facilities/alma/science_sustainability/URSI.pdf.

27 The *ALMA Development Roadmap*, J. Carpenter et al. (The ALMA Development Working Group) can be found at: www.almaobservatory.org/wp-content/uploads/2018/07/20180712-alma-development-roadmap.pdf.